



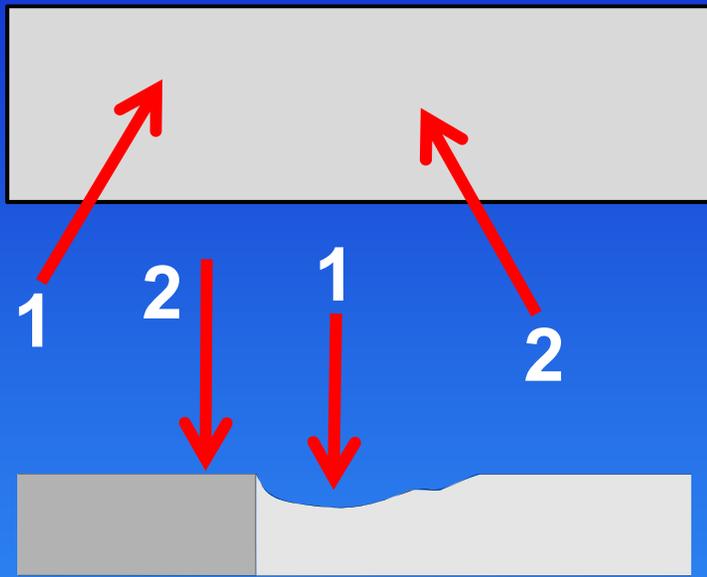
Corrosion and Corrosion Control in LWRs Summary



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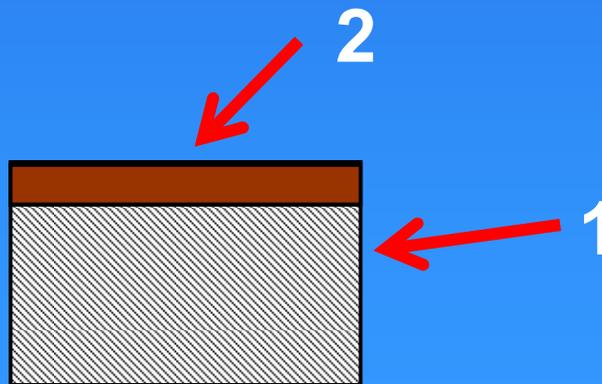
Identify the Anodes and Cathodes

Identify the Anodes and Cathodes



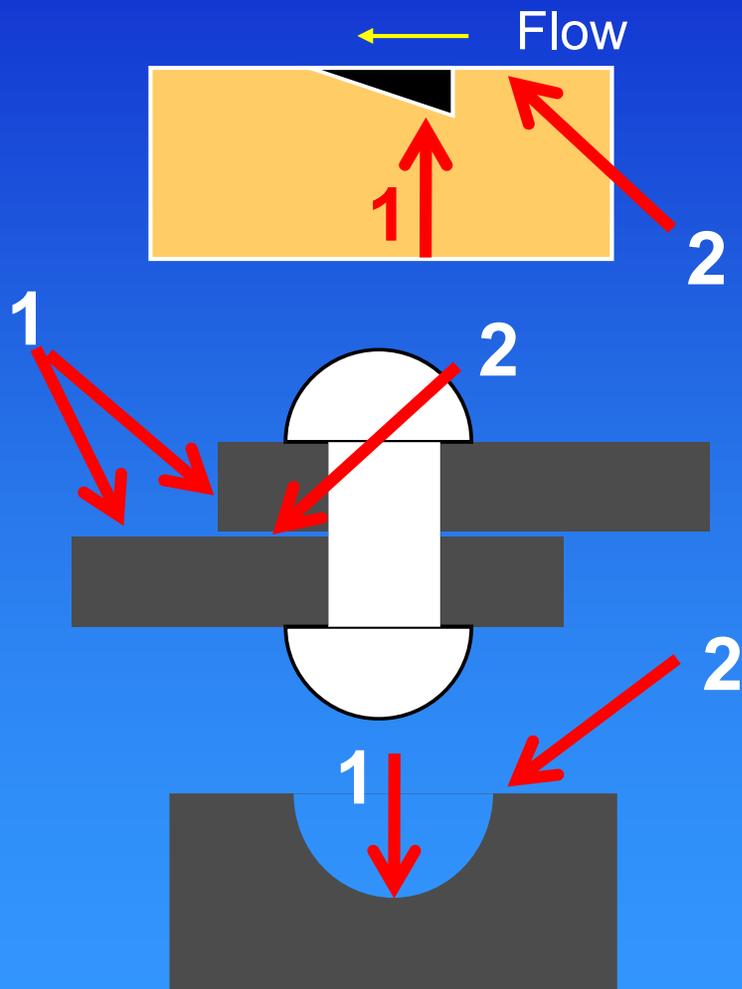
- General Corrosion

- Galvanic Corrosion



- Dealloying Corrosion

Identify the Anodes and Cathodes

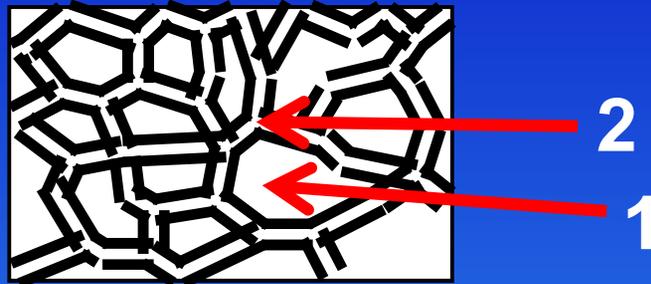


- Velocity Phenomena

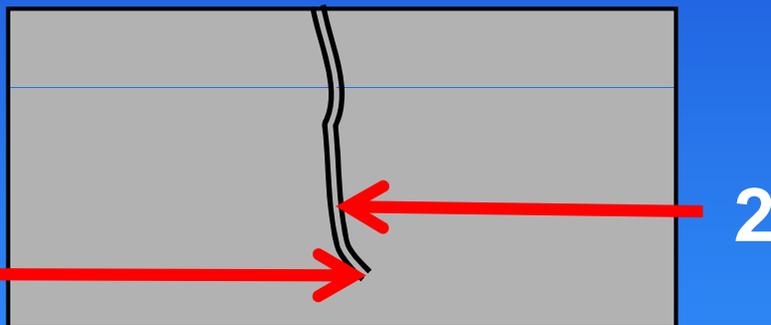
- Crevice Corrosion

- Pitting Corrosion

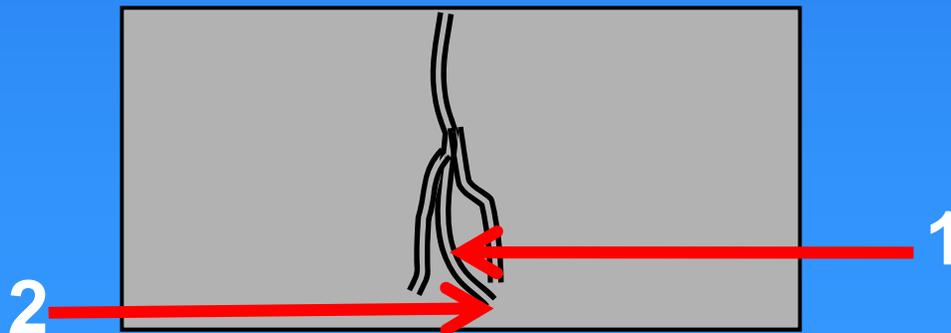
Identify the Anodes and Cathodes



- IGA



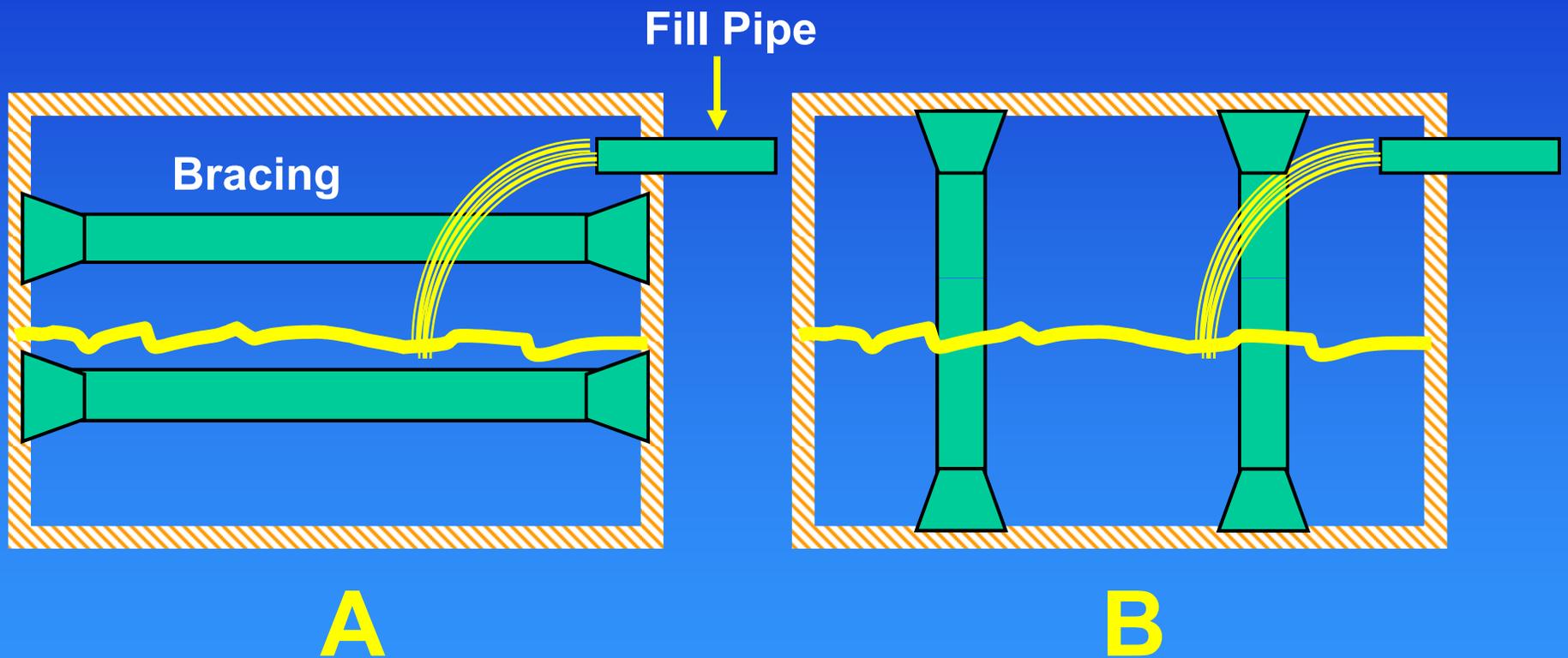
- Corrosion Fatigue



- SCC

Corrosion Design Considerations

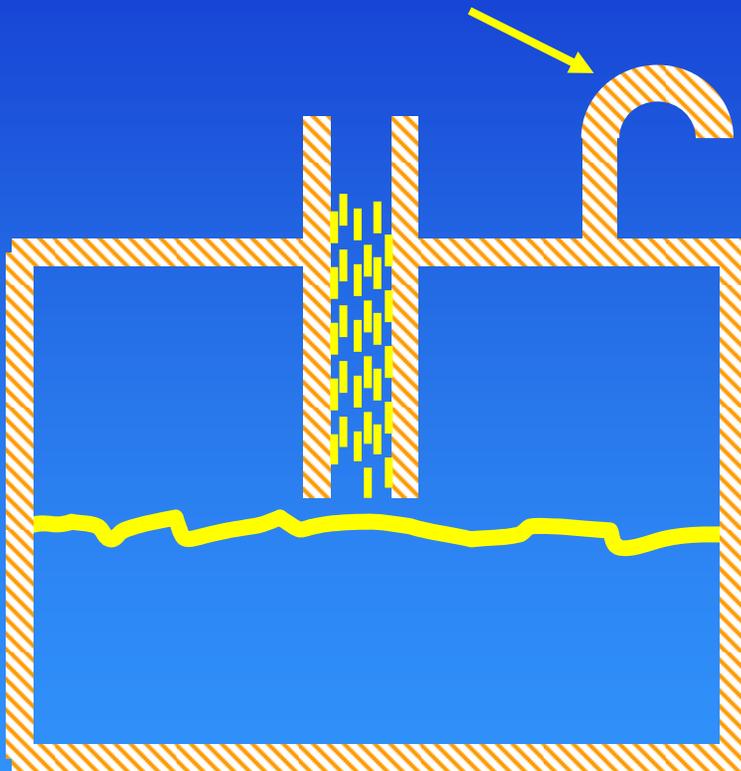
Best Corrosion Design: A or B?



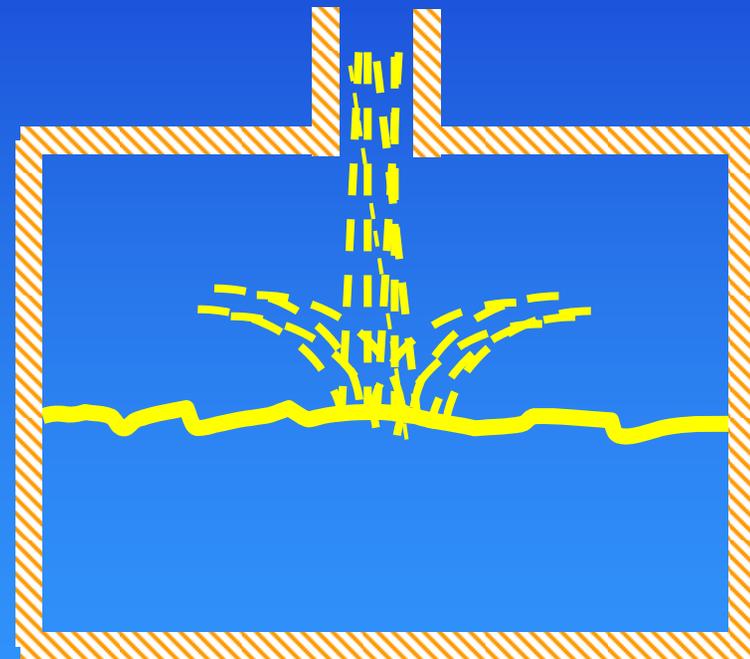
V. Pludek, Design and Corrosion Control, 1977

Best Corrosion Design: A or B?

Air pipe or safety valve



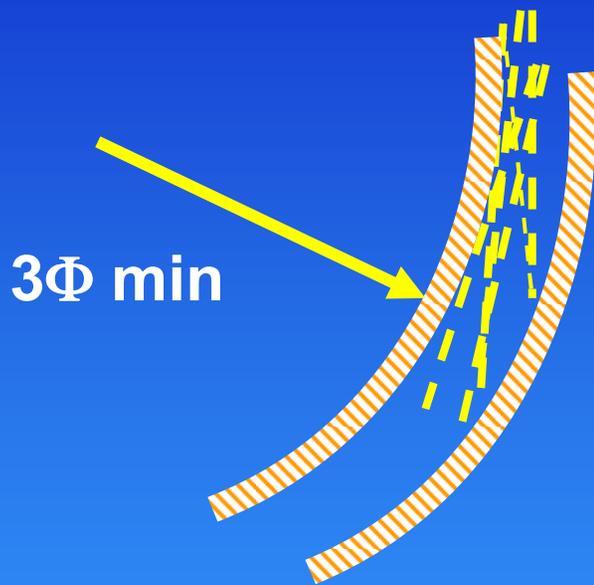
A



B

V. Pludek, Design and Corrosion Control, 1977

Best Corrosion Design: A or B?



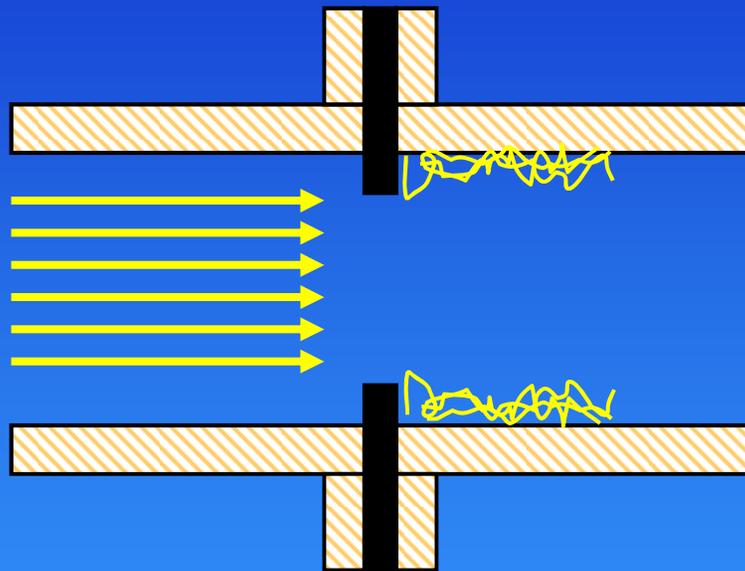
A



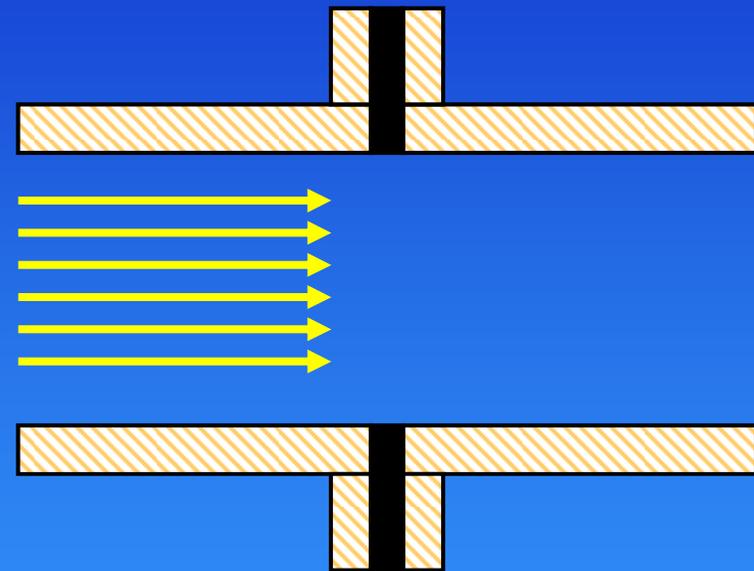
B

V. Pludek, Design and Corrosion Control, 1977

Best Corrosion Design: A or B?



A

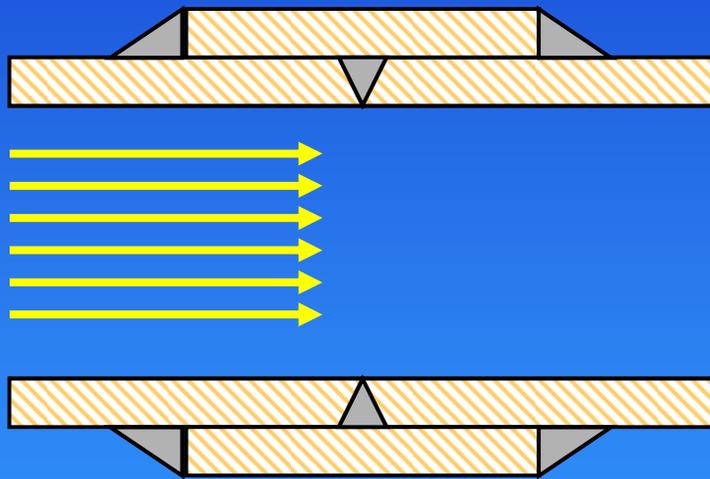


B

V. Pludek, Design and Corrosion Control, 1977

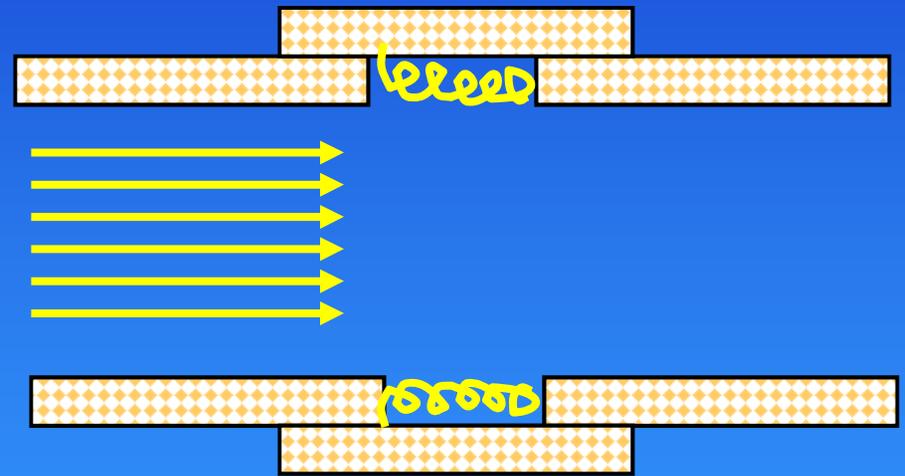
Best Corrosion Design: A or B?

welded joint



A

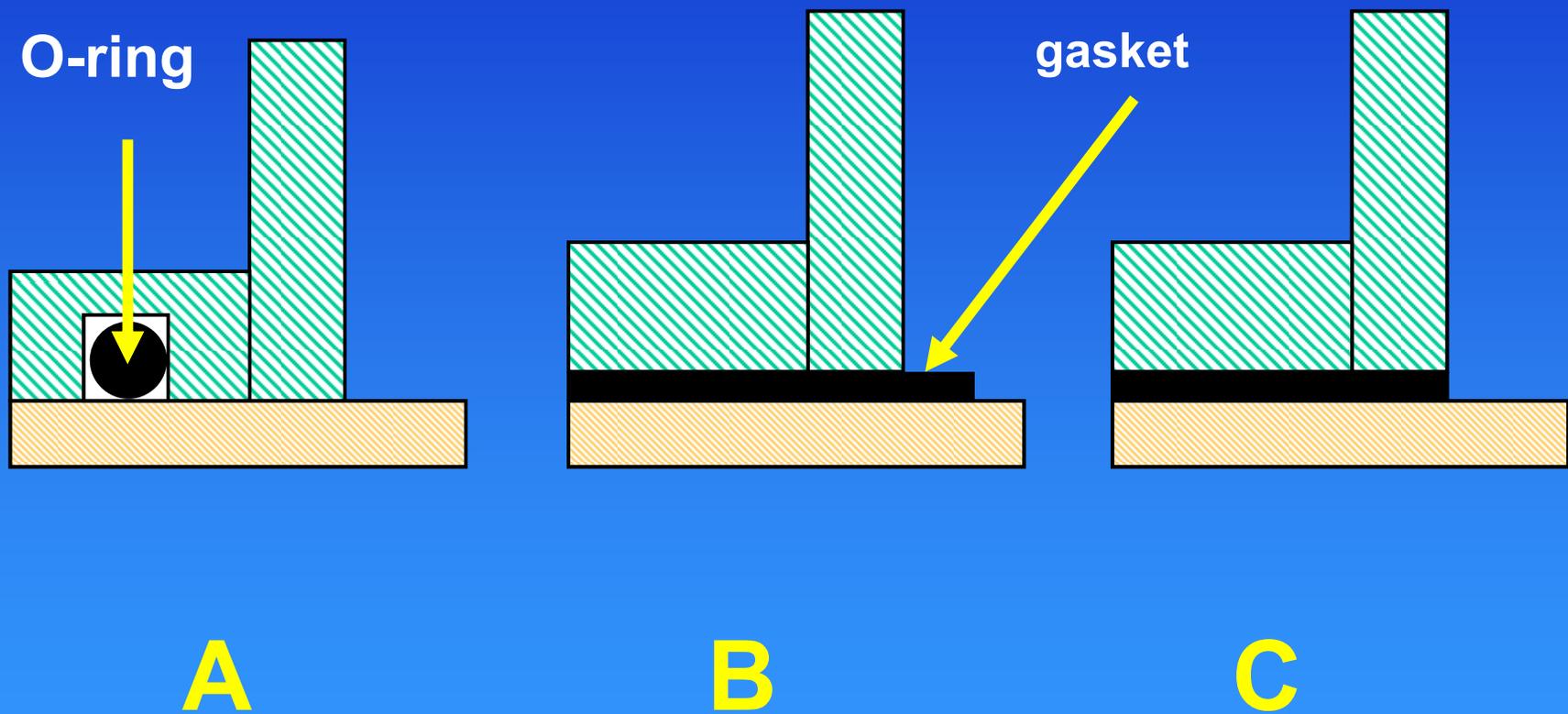
screwed joint



B

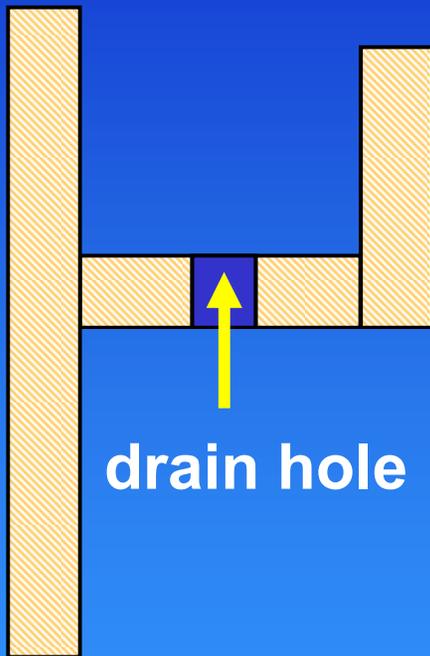
V. Pludek, Design and Corrosion Control, 1977

Best Corrosion Design: A, B or C?

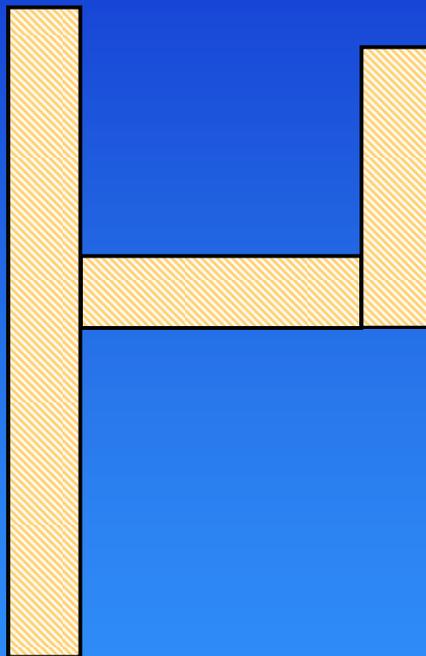


V. Pludek, Design and Corrosion Control, 1977

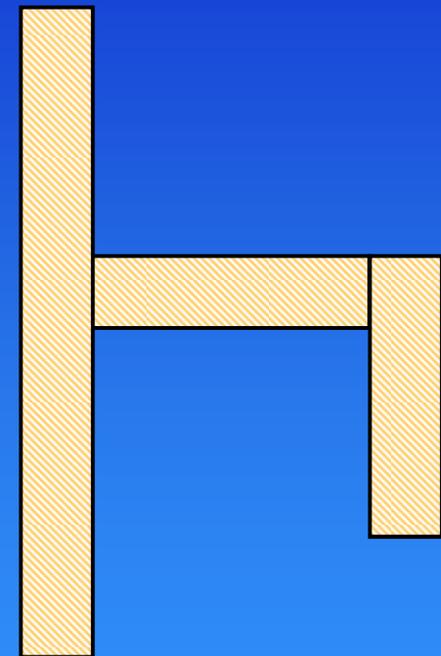
Best Corrosion Design: A, B or C?



A



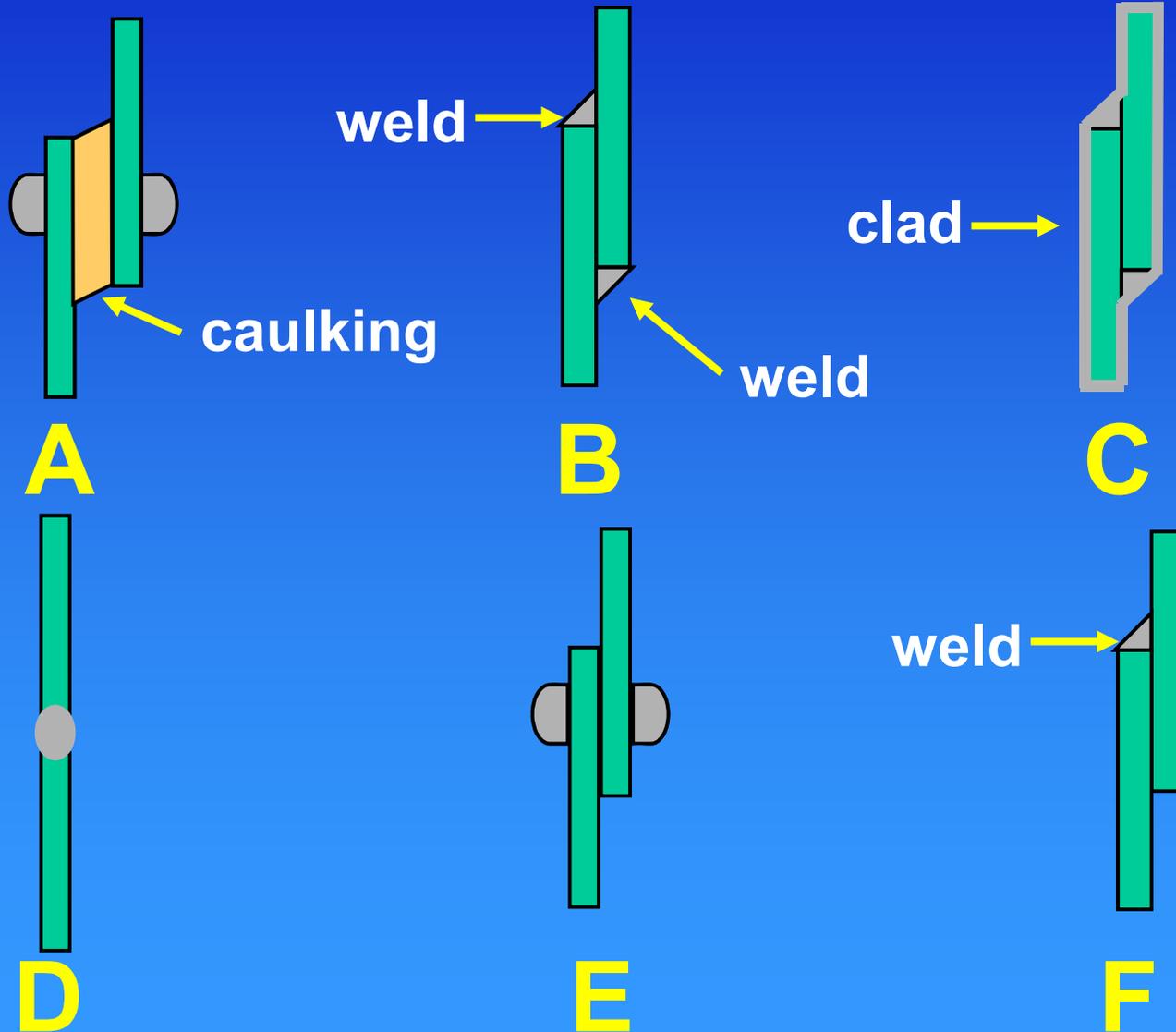
B



C

V. Pludek, Design and Corrosion Control, 1977

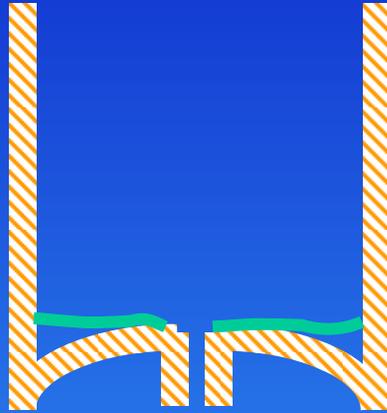
Best Corrosion Design: A, B, C, D, E or F?



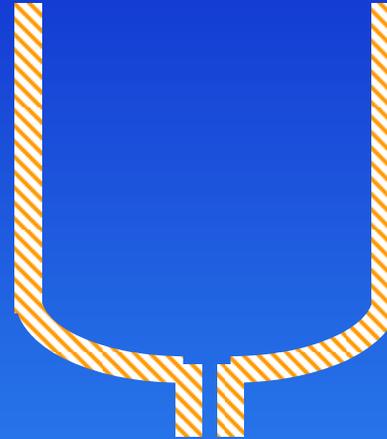
V. Pludek,
Design and
Corrosion
Control, 1977

Best Corrosion Design: A, B, C or D?

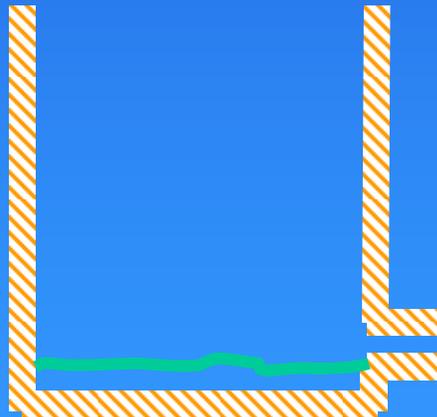
A



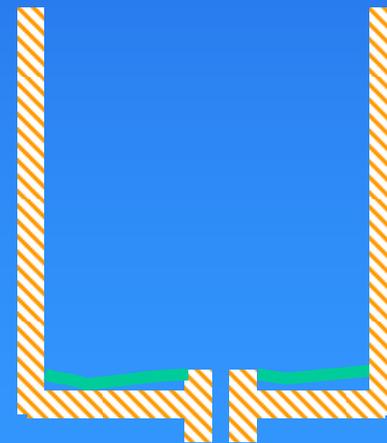
B



C



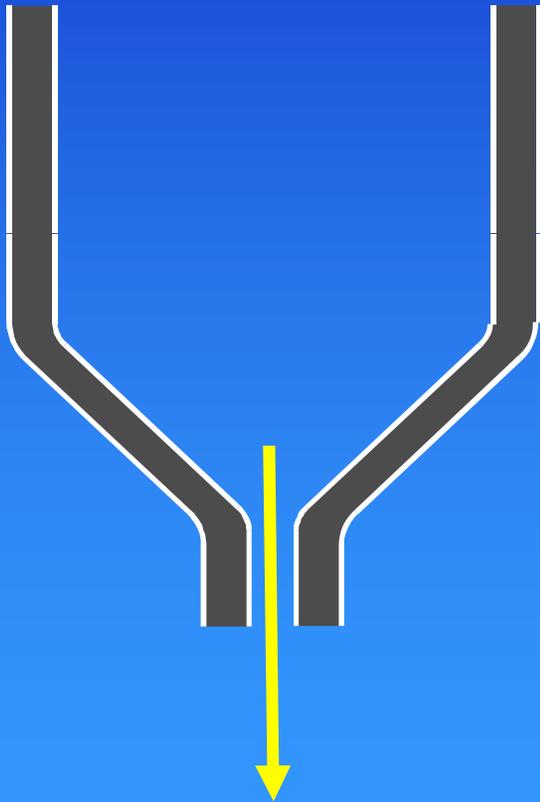
D



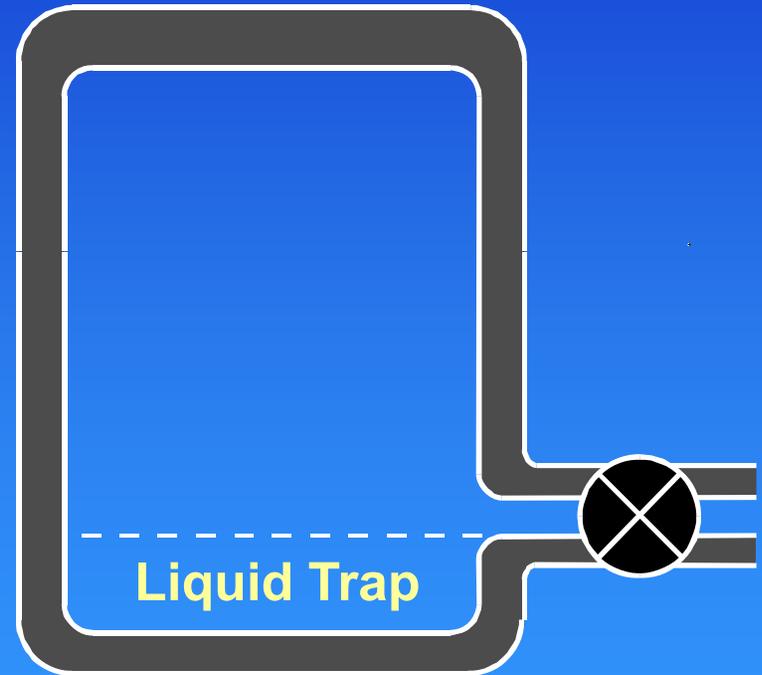
V. Pludek, Design and Corrosion Control, 1977

Best Corrosion Design: A or B?

A

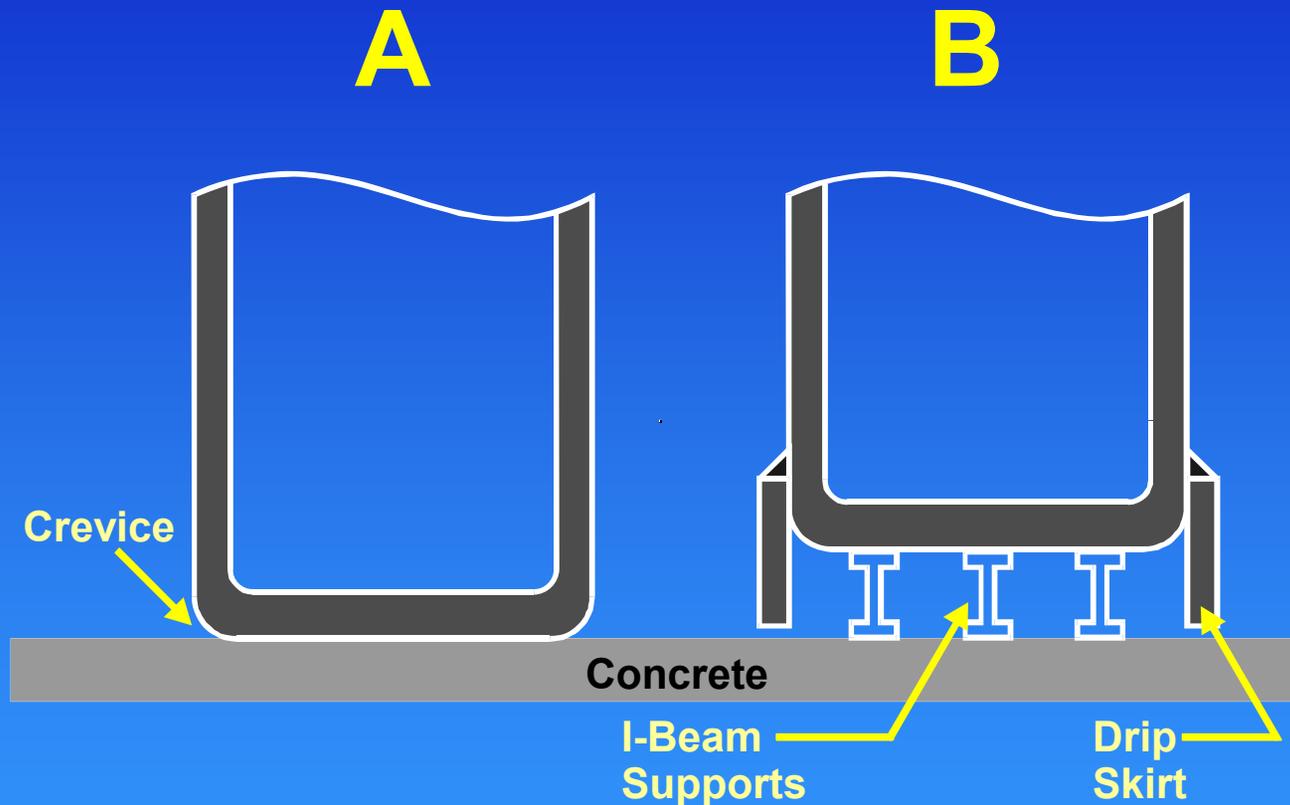


B



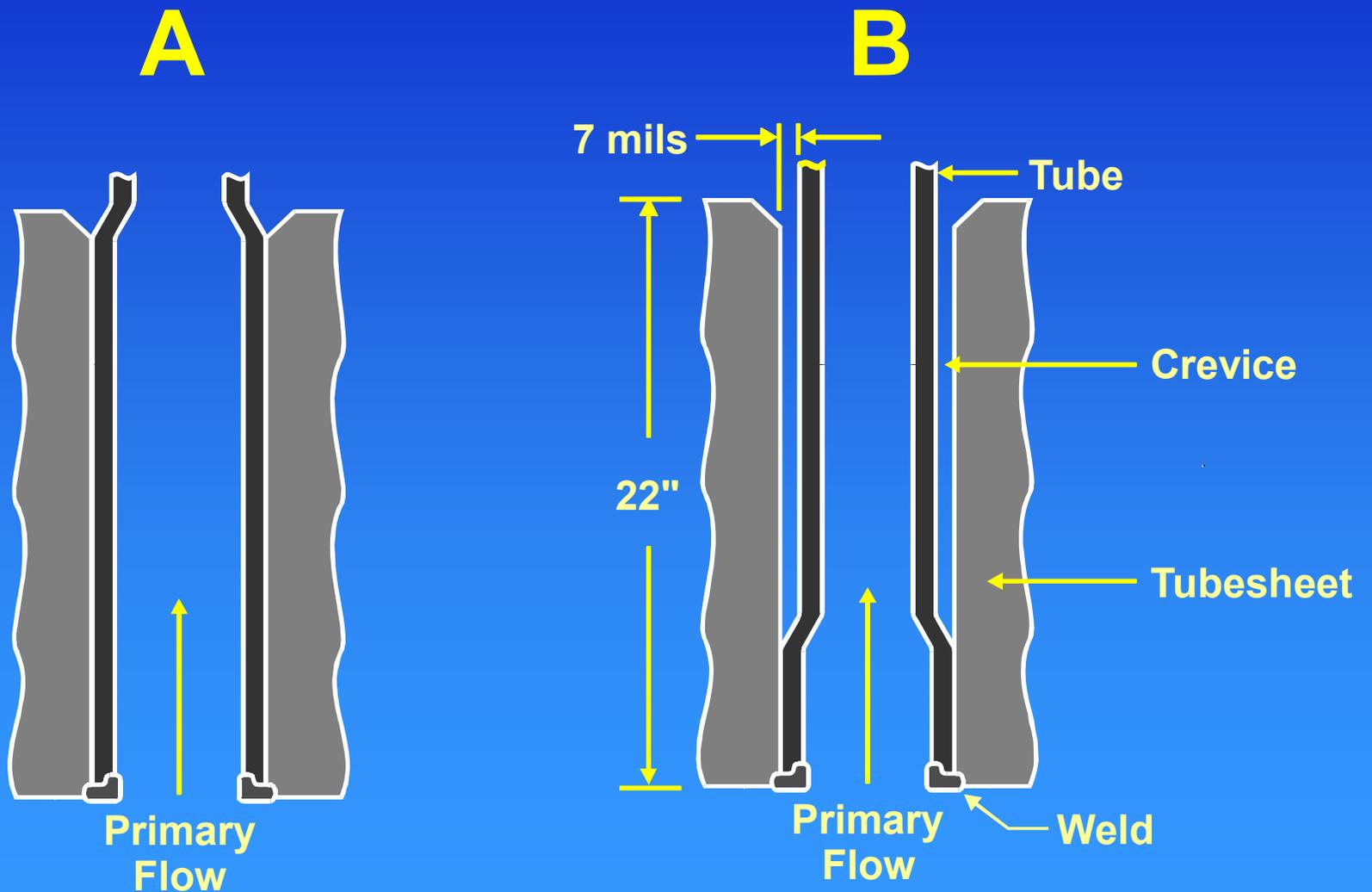
D. Jones, Principles and Prevention of Corrosion, 1992

Best Corrosion Design: A or B?



R. Landrum, Fundamentals for Designing for Corrosion Control, 1989

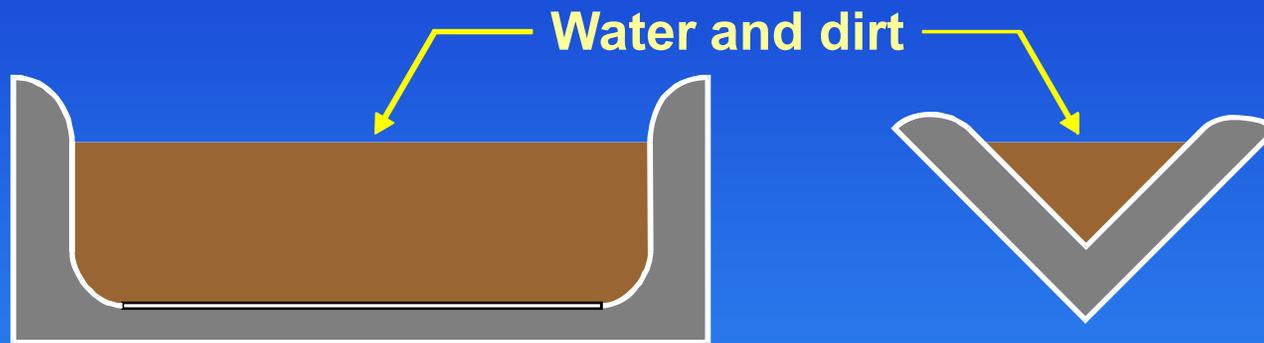
Best Corrosion Design: A or B?



D. Jones, Principles and Prevention of Corrosion, 1992

Best Corrosion Design: A or B?

A

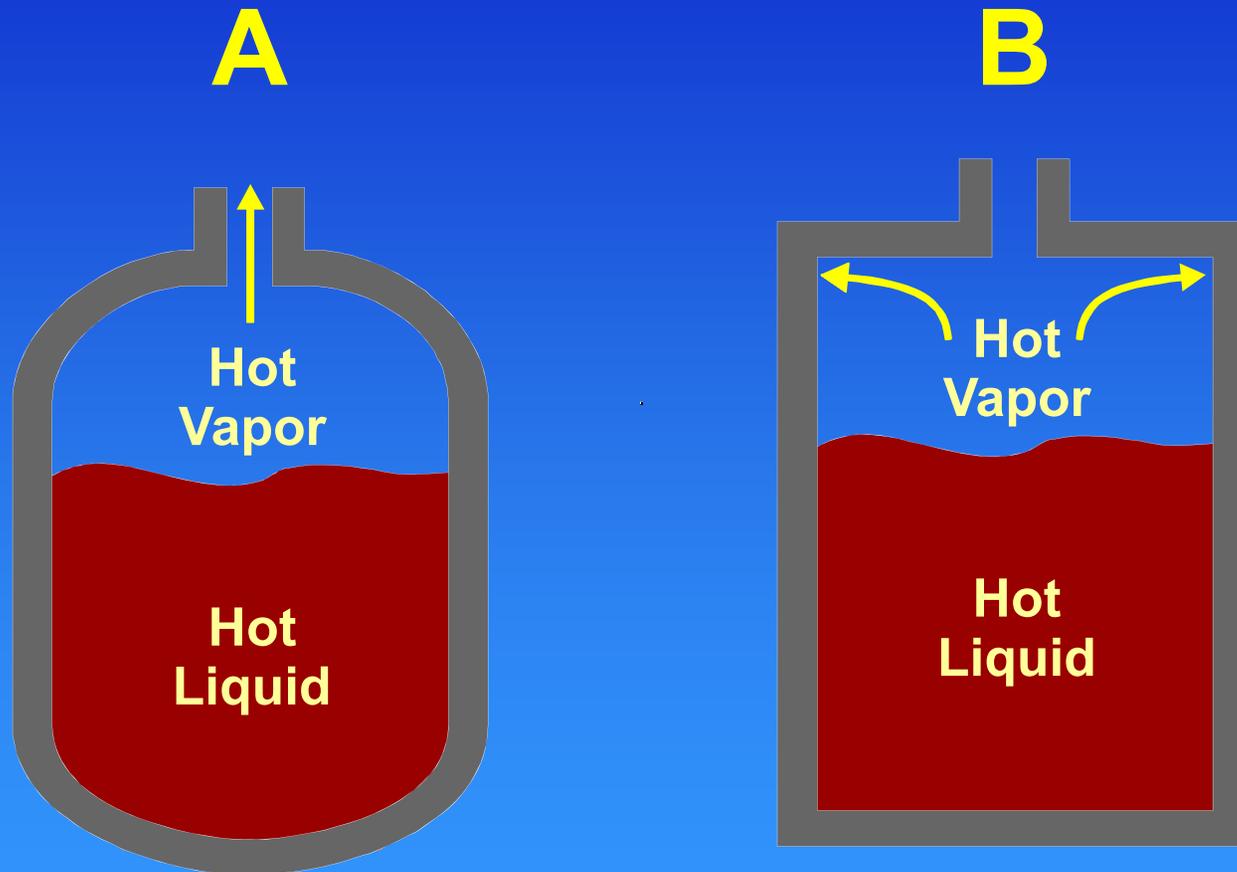


B



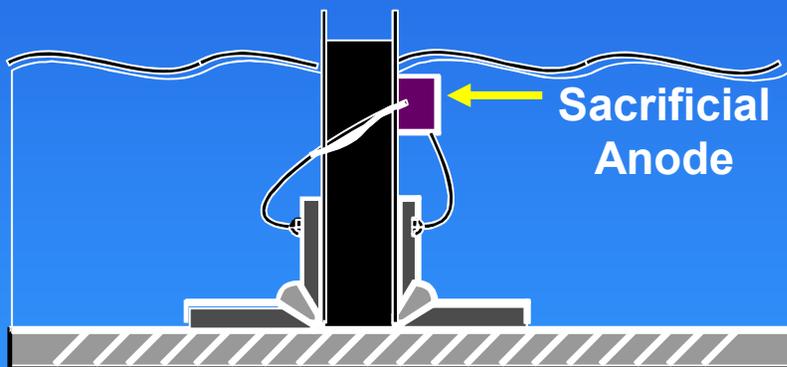
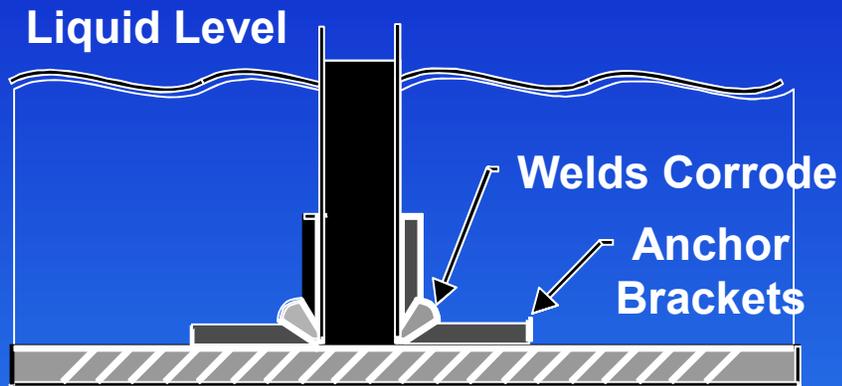
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Best Corrosion Design: A or B?

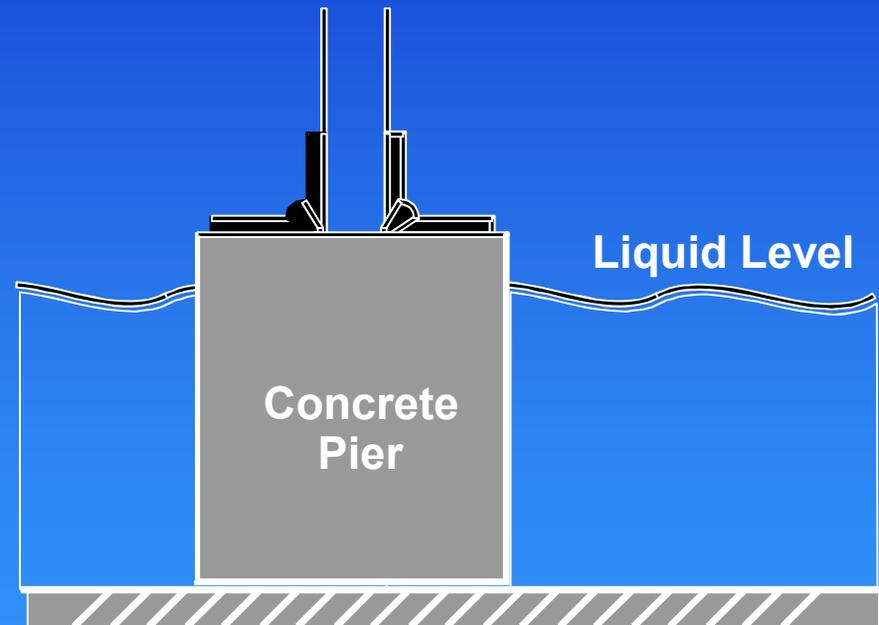


D. Jones, Principles and Prevention of Corrosion, 1992

Best Corrosion Design: A or B?



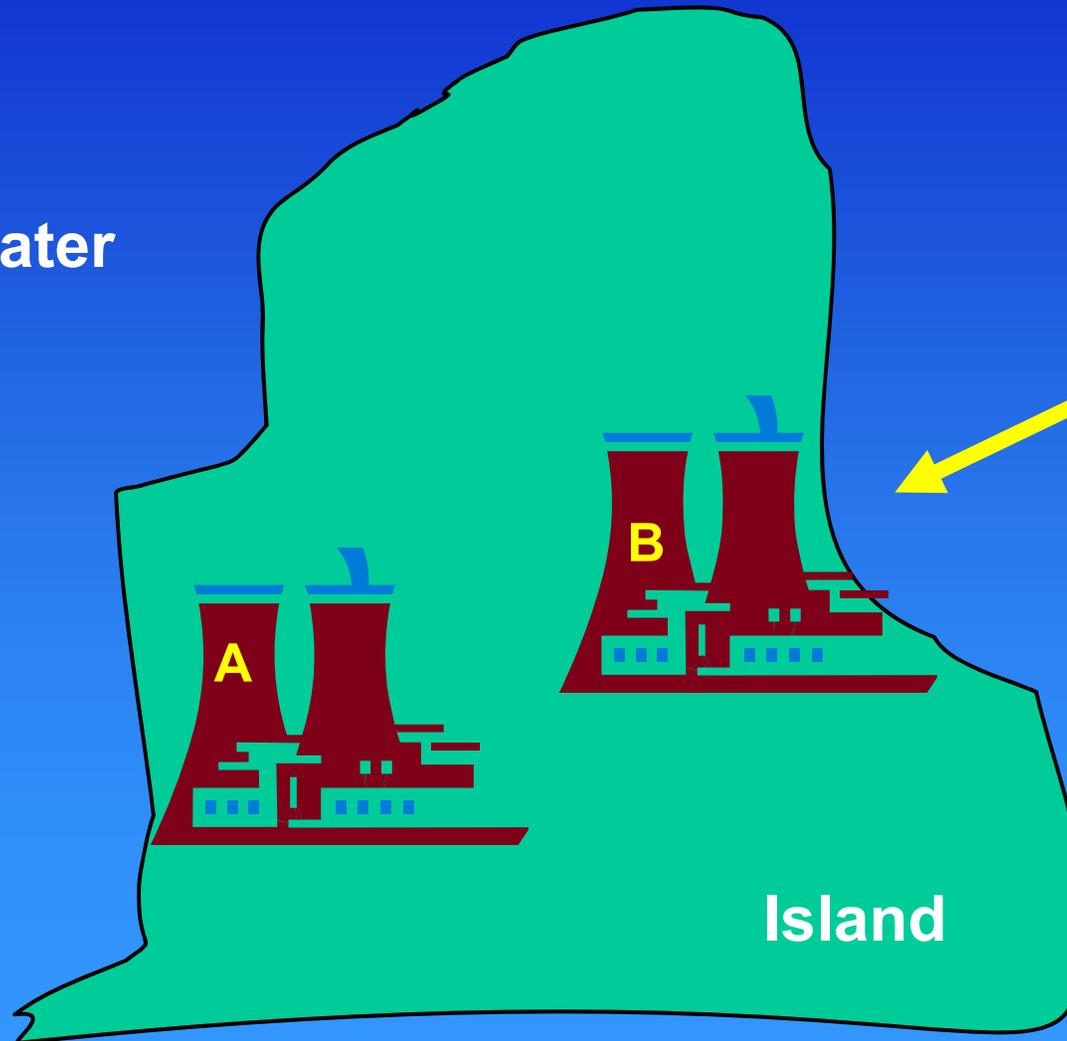
A



B

Where would you locate your reactor? Why?

Seawater

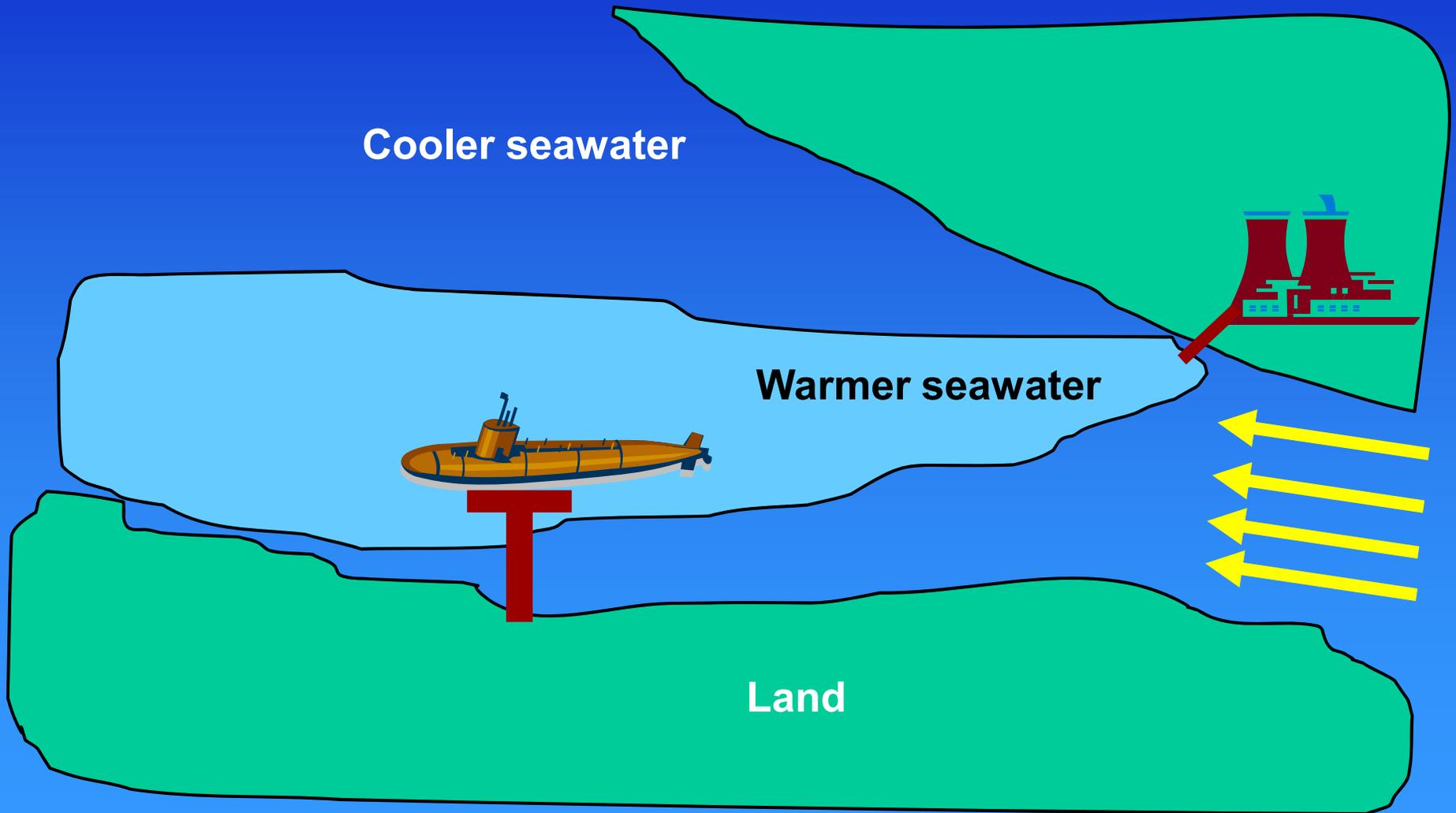


Prevailing
Winds

Seawater

Island

Corrosion performance of the sub?



Corrosion Quiz

LWR Corrosion True or False

1. Mo is an alloying element in Type 316 Nuclear Grade stainless steel
2. Alloy 600 is susceptible to boric acid corrosion in PWRs
3. Cutting, bending and grinding can be sources of cold work which generally increase stainless steel's and Alloy 600's resistance to IGSCC and PWSCC, respectively
4. FAC affects carbon steels in both BWRs and PWRs
5. Chloride and sulfate anions can promote such corrosion phenomena as crevice corrosion and SCC

LWR Corrosion True or False

1. PWR SG tubing suffer from most forms of corrosion
2. Crevices cause corrosion concerns in all LWRs
3. The mechanism for PWSCC in Ni-base alloys is well understood
4. Annealing is a main source of cold work in BWRs and PWRs
5. IGA is usually characterized by more reactive grain boundary regions
6. Addition of Zn to the coolant appears to be a promising IGSCC and PWSCC mitigation technique
7. Mechanism of boric acid corrosion of PWR top heads is well understood

LWR Corrosion True or False

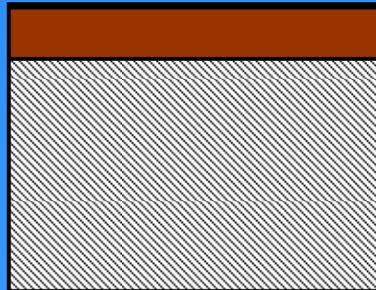
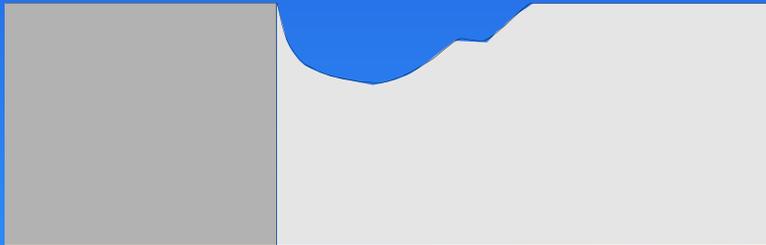
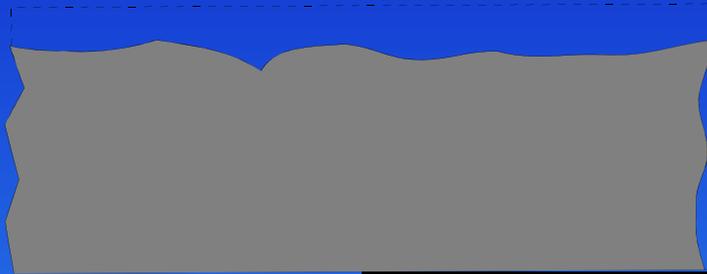
1. Corrosion potential of noble metal deposited stainless steel dramatically decreases when the molar ratio of H_2 to O_2 is >1
2. Neutron fluence dramatically affects the microstructure of reactor vessel internals
3. Laser peening and water jet peening appear promising for mitigation IGSCC and IASCC in LWRs
4. Sensitization in stainless steel is characterized by the precipitation of chromium carbides (e.g., $Cr_{23}C_6$) in the grain interiors
5. Weld overlays are a SCC mitigation/repair technique that are applicable to both BWRs and PWRs

LWR Corrosion True or False

1. Degradation of BWR and PWR internals is the most challenging materials corrosion problem the LWRs has faced to date
2. Good quality BWR and PWR water chemistry should be maintained to minimize corrosion costs
3. Perhaps the most common source of tensile stress for IGSCC and PWSCC is welding residual stress
4. Decreasing the carbon content of austenitic stainless steel increases its resistance to sensitization
5. Reduction of the conductivity of water to theoretically low levels ($\sim 0.055 \mu\text{S}/\text{cm}$) will eliminate IGSCC in the BWR
6. If only one of the three necessary conditions for SCC is eliminated, SCC can still occur

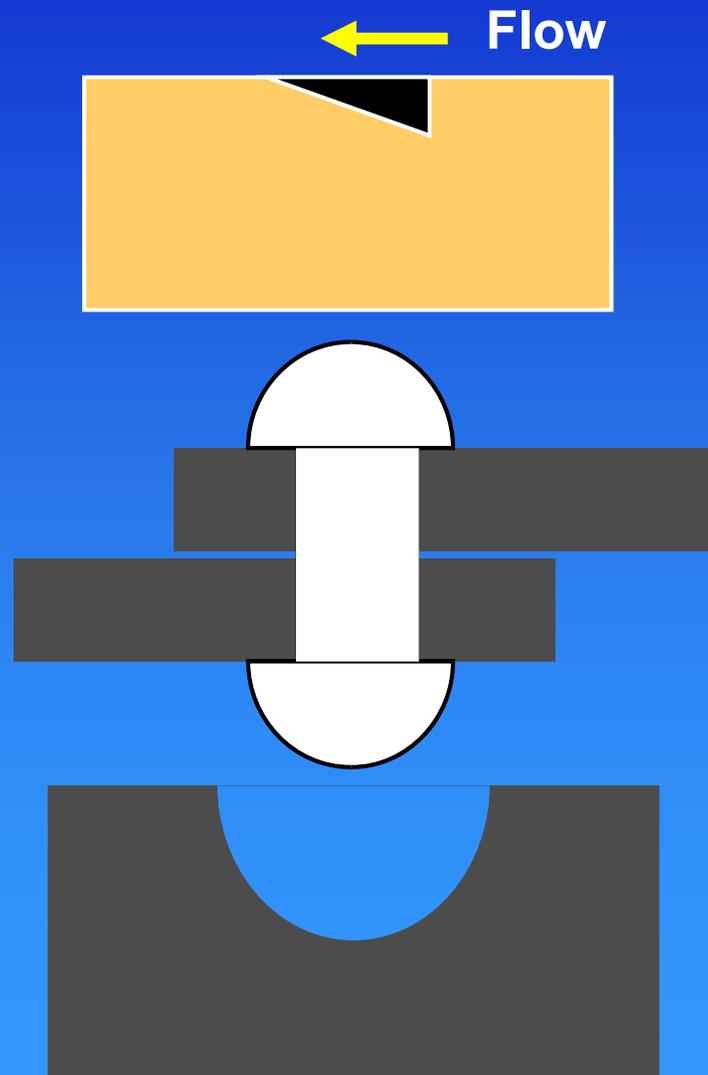
LWR Corrosion Case Study Review

LWR Corrosion Case Study Summary



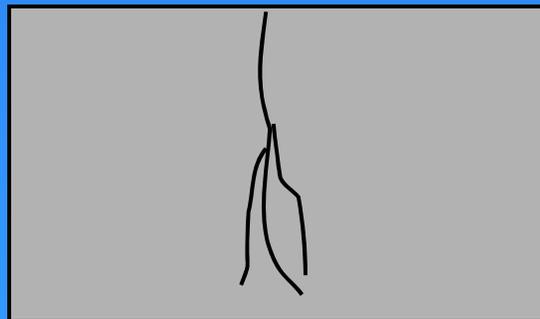
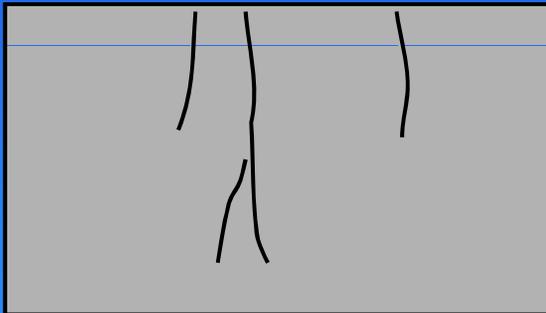
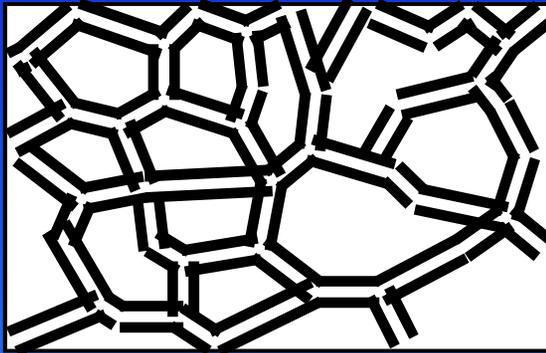
- **General Corrosion**
 - ◆ BAC of CS/LAS
 - ◆ Alloy X-750
 - ◆ LWR drywells
 - ◆ Zr alloys
- **Galvanic Corrosion**
 - ◆ Condenser tubes/support plate
 - ◆ Cr depleted zones
- **Dealloying Corrosion**
 - ◆ Condenser support plate

LWR Corrosion Case Study Summary



- **Velocity Phenomena**
 - ◆ Erosion - BAC of LAS
 - ◆ FAC
 - ◆ Condenser tubes
- **Crevice Corrosion**
 - ◆ SG tubes
 - ◆ Safe ends
- **Pitting Corrosion**
 - ◆ Condenser tubes

LWR Corrosion Case Study Summary



- **IGA**
 - ◆ SG tubes
 - ◆ Decontamination solutions
- **Corrosion Fatigue**
 - ◆ BWR feedwater nozzles
 - ◆ BWR steam dryer
 - ◆ PWR SG FW nozzle
- **SCC**
 - ◆ BWR piping
 - ◆ Alloy 600/182/82 PWSCC
 - ◆ IASCC

BWR Corrosion Summary

(For your reading pleasure)

BWR RCS Components and Environments

- BWR RCS components include the RPV, core internals (e.g., shroud, jet pump), ECCS connections, steam dryer/separator and recirculation piping
- During full power operation these components are exposed to high purity reactor water and/or wet steam at 232-288°C (450-550°F)
- ECP of these components depends on NWC/HWC and location
- Some of the internal components are exposed to neutron fluxes that produce fluences (up to 10 dpa) at the end of the original 40 year plant design life

Current RCS BWR Corrosion Concerns

- Major BWR corrosion concern is IGSCC
 - ◆ IGSCC of Alloy 182 weldments used in joints between ferritic and austenitic components (e.g., thermal sleeves, attachment pads)
 - ◆ IG/IASCC of Type 304/316 SS HAZs (even under HWC) at moderate fluences
 - ◆ IGSCC of Alloy 600 components and HAZs throughout RCS, particularly under NWC
 - ◆ IGSCC of Alloy X-750 components throughout the RCS under both NWC and HWC
- CS and LAS components and welds exposed to suppression pool water susceptible to crevice corrosion, general corrosion, pitting and SCC
- CS to brass joints in the drywell are susceptible to galvanic corrosion and crevice corrosion

BWR Emergency Core Cooling System

- Includes the low and high-pressure core spray lines, the condensate storage tank and the RHR piping and subsystems
- Few BWR ECCS components have a high corrosion susceptibility than in RCS because these CS and LAS systems operate in condensate cooling water or suppression pool water at low temperatures $<38^{\circ}\text{C}$ (100°F)
- However, the generally poor quality water, especially in the suppression pool increases the susceptibility to pitting corrosion
- Depending on DOS, Type 304/316 SS HAZs are susceptible to SCC in these systems with no HWC
- CS to brass joints in the drywell are susceptible to galvanic corrosion and crevice corrosion

BWR Steam and Power Conversion Systems

- Includes the main steam and feedwater lines, main condenser and its associated piping. The components in these subsystems are primarily CS and LAS and are exposed to steam, condensate or demineralized water. The following corrosion mode combinations may have corrosion susceptibility:
 - ◆ Pitting and SCC of LAS bolts for the T-quencher/sparger above the suppression pool
 - ◆ Outside surfaces of Ti condenser tubes are susceptible to droplet erosion if directly exposed to incoming wet steam.
 - ◆ CF of CS weldolets and the possible SCC in saturated steam at 286°C (547°F) in the main steam line

BWR Support and Auxiliary Systems

- CS and SS exposed environments ranging from wet steam at 286°C (547°F) to suppression pool water at <38°C (<100°F)
- Corrosion forms include general corrosion, pitting corrosion, SCC and crevice corrosion
- The following component corrosion form combinations have high susceptibility:
 - ◆ CF of CS socket welds in 286°C (547°F) steam
 - ◆ Crevice corrosion of ferritic valve components exposed to oxygenated suppression pool water with poor chemistry control
 - ◆ SCC adjacent to Type 304/316 SS weldments in the RWCU piping to pumps with water at 279°C (535°F) under NWC

Potential BWR Corrosion Concerns

- Long-term effects of HWC on SCC are not yet clear
- Low ECPs needed for mitigation are not achieved at all the high-susceptibility locations
- CF of austenitic SSs and Ni alloys at low ECPs under HWC conditions
- SCC of severely cold worked or mechanically-strained stainless steels in BWR water
- Abusive grinding or machining during weld preparation or surface finishing and their adverse effects on SCC and CF crack initiation

PWR Corrosion Summary

(For your reading pleasure)

PWR RCS Components and Environments

- PWR RCS includes the pressurizer, RPV and its internals, the reactor coolant pump, the primary and secondary sides of SG and piping subsystems
- PWR RCS piping subsystems are the cold leg piping, crossover leg piping, hot leg piping, pressurizer spray piping, pressurizer surge piping, pressurizer piping to power operated relief valves, pressurizer piping to safety relief valves and stop valve loop bypass piping
- Most of the components in the primary side of the PWR RCS are exposed to primary water at 288-327°C (550-620°F), but some of the pressurizer and pressurizer-piping components are exposed to saturated steam/condensate up to ~343°C (650°F)

PWR RCS Components and Environments

- RPV internal components are also exposed to neutron fluxes that can result in moderate or high neutron fluences as high as 80 dpa at 40 years original reactor life
- Components on the secondary side of SG operate at 293-315°C (560-600°F), steam and a variety of aqueous environments that may have been used at various times in the operating life; in all cases, aggressive environments can form in some locations such as crevices, heat transfer surfaces, etc.

Current PWR RCS Corrosion Concerns

- PWSCC of Alloy 82/182 weldments throughout the primary system and especially in the highest temperature components such as the pressurizer
- SCC of Alloy 600MA and 600TT SG tubes and Alloy 600 forged components and cold worked material such as SG tube expansion transitions, small radius U-bends and the high-temperature components of the pressurizer
- BAC of LAS components originating from primary water leaks, specifically in the annuli between the Alloy 600 penetrations and the LAS RPV or pressurizer

Current RCS PWR Corrosion Concerns

- IASCC of austenitic stainless steels at more than 0.5 dpa, (e.g., baffle bolts and other high strength fasteners) and swelling in internals components that reach higher temperatures and much higher doses
- CF due to unanticipated vibration and thermal fluctuations (e.g., in socket welds), which occur throughout the RCS, primary circuit deadlegs and baffle bolts after irradiation-induced relaxation of pre-stress

PWR Emergency Core Cooling System

- Fewer components with a high susceptibility than in RCS, since these systems typically operate at significantly lower temperatures than the RCS
 - ◆ SCC of dissimilar metal Alloy 82/182 weldments in piping connected to the RCS cold leg of CE and B&W plants. Such components operate at 291-345°C (556-653°F) in primary water have a high susceptibility to SCC. Some of the dissimilar metal weldments in this system are of Type 308/309 stainless steel and have much lower susceptibility.
 - ◆ CF of socket welds throughout the ECCS due to thermal stresses and FIV
 - ◆ SCC of cast stainless steel components (e.g., RHR pump suction piping)

PWR Steam and Power Conversion Systems

- Includes the main steam, main feedwater, auxiliary feedwater and SG blowdown subsystems fabricated from CS and LAS that are exposed to steam, condensate or demineralized water
- Corrosion degradation modes are FAC of CS and CF of LAS and CS components, welds and HAZs

PWR Support and Auxiliary Systems

- Includes the service water, chemical and volume control (CVCS), component cooling water (CCW) and spent fuel pool subsystems fabricated from CS, Cu alloys and SSs exposed to untreated and treated water or primary water at relatively low temperatures
- Pitting corrosion and crevice corrosion of buried CS piping and penetrations through concrete and of Cu-Zn heat exchanger tubing
- Fatigue of socket welds throughout the support systems, but especially in the CVCS system due to unanticipated FIV
- SCC of Cu-Zn brass heat exchanger tubing used in the service pump water discharge piping

Potential PWR Corrosion Concerns

- Although Alloy 690TT has exhibited good SCC resistance compared with Alloy 600 MA during more than 16 years of use in SG tubing, its long-term resistance in other PWR primary water applications (e.g., RPV penetrations) is unknown
- Potential degradation increases when cold worked and the use of the alternate welding alloys (Alloys 52 and 152) that suffer welding challenges such as lack of fusion and ductility dip cracking
- SCC of severely mechanically-strained stainless steels in PWR primary water, e.g., weld shrinkage strains in HAZs, pressurizer heater cladding and cold-bent piping elbows

Potential PWR Corrosion Concerns

- SCC of SG tubes by corrosive species (e.g., Pb and S ions) not previously appreciated to be widespread in the secondary system and which may also affect as Alloy 690 tubing
- Potential degradation related to end of fuel cycle primary water chemistry, especially during cycle stretch-out, when the concentration of BA may be reduced below the minimum recommended value, thereby leading to possible localized corrosion due to excess LiOH (e.g., the boiling crevices in the pressurizer)
- Accelerated environmental effects on fatigue of austenitic stainless steels and Ni alloys at low ECPs